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Space systems — Space solar cells — Electron and proton irradiation test methods

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Contents

Page

Foreword.....	iv
Introduction	v
1 Scope	1
2 Normative references	1
3 Terms and definitions	1
4 Symbols and abbreviated terms	2
5 Space radiation environments	2
5.1 Space radiation	2
5.2 Shielding effects	2
6 General radiation effects in solar cells.....	3
6.1 Solar cell radiation damage.....	3
6.2 Radiation effects on solar cell cover	3
7 Radiation test methods	3
7.1 General	3
7.2 Electron irradiation.....	4
7.2.1 Temperature	4
7.2.2 Coverage area	4
7.2.3 Irradiation beam uniformity	4
7.2.4 Flux levels	5
7.2.5 Vacuum.....	5
7.2.6 Dosimetry	5
7.3 Proton irradiation.....	5
7.3.1 General	5
7.3.2 Coverage area	5
7.3.3 Vacuum.....	5
7.4 Annealing	5
8 Test report	6
Bibliography.....	7

Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 2.

The main task of technical committees is to prepare International Standards. Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

ISO 23038 was prepared by Technical Committee ISO/TC 20, *Aircraft and space vehicles*, Subcommittee SC 14, *Space systems and operations*.

Introduction

This standard provides general test methods for the electron and proton irradiation testing of space solar cells. For this document, single-junction and multi-junction solar cells are included. This standard address only test methods for performing irradiation of space solar cells and not the method for data analysis.

Space systems — Space solar cells — Electron and proton irradiation test methods

1 Scope

This international standard specifies the requirements for electron and proton irradiation test methods of space solar cells.

2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 15387¹⁾, *Space systems — Single-junction space solar cells — Measurement and calibration procedures*

ISO 23039¹⁾, *Space systems — Multi-junction space solar cells — Calibration procedures*

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

3.1

differential energy spectrum

the spread of energies of some specific group.

NOTE In this document, this refers to the number of particles possessing an energy value that lies in the infinitesimal range between E and $E+dE$. Integration of the differential particle spectrum over all particle energies yields the total number of particles. This quantity is given in units of particles per unit area per unit energy.

3.2

electrons (e)

elementary particles of rest mass $m = 9,109 \times 10^{-31}$ kg, and having a charge of $1,602 \times 10^{-19}$ coulomb

3.3

flux

the number of particles passing through a given area in a specified time, usually given in particles cm^{-2} second⁻¹

NOTE Flux may also be specified in terms of the number of particles per unit time passing through an area on the surface of a sphere enclosed by a solid angle. The units are particles $\cdot \text{cm}^{-2} \cdot \text{second}^{-1} \cdot \text{sr}^{-1}$, where a steradian (sr) is defined as the solid angle, which encloses a surface on a sphere equal in area to the radius of the sphere squared.

3.4

fluence

the total number of photons or particles in any given time period given in units of particle per unit area

1) To be published

NOTE Fluence is also known as time-integrated flux.

3.5

integral energy spectrum

the total number of particles in a specified group that possess energies greater than, or equal to, a specified value, given in units of particles per unit area

3.6

irradiation

exposure of a substance to energetic particles or photons that penetrate the material and have the potential to transfer energy to the material

3.7

omnidirectional flux

the number of particles of a particular type that would transverse a test sphere of 1 cm^2 cross-sectional area in 1 second (particles $\cdot \text{cm}^{-2} \cdot \text{second}^{-1}$)

3.8

protons (p^+)

positively charged particles of mass number one (having a mass of $1,672 \times 10^{-27} \text{ kg}$) and a charge equal in magnitude to the electron

NOTE A proton is the nucleus of a hydrogen atom.

4 Symbols and abbreviated terms

eV electron volt,

NOTE a unit of energy commonly used for ion, electrons, elementary particle, etc. $1 \text{ MeV} = 1,602 \times 10^{-19} \text{ joules}$.

NIEL nonionizing energy loss,

NOTE The rate at which the incident particle transfers energy to the crystal lattice through nonionizing events is referred to as the nonionizing energy loss (NIEL) $\text{cm}^2 \cdot \text{MeV/g}$.

5 Space radiation environments

5.1 Space radiation

Primarily electrons and protons with a wide range of energies characterize the space radiation environment. Alpha particles and other charged particles are usually of negligible quantity as far as solar cell damage is concerned. The particles come from the solar wind and are trapped by Earth's magnetic field to form radiation belts with widely varying intensities [1]. The inner portion of the belts consists mainly of protons while the outer portion consists primarily of electrons. Outside of these radiation belts, there is a likelihood of sudden bursts of protons originating from coronal mass ejections from the Sun, referred to generally as solar flares. Thus, the differential spectrum of electrons and protons for any given mission is dependent on the specific mission orbit. Due to the large variability of the involved phenomena the prediction of the particle spectrum for a given mission is affected by a significant uncertainty. The most widely accepted tools for its calculation are the AP8 and AE8 codes developed by NASA.

5.2 Shielding effects

Space solar cells are typically flown with some material covering the cell surface, most typically a piece of glass (coverglass), and are mounted on some support structure. These front and rear covering material act to shield the solar cell from some of the incident irradiation. Because of this, the solar cell is actually irradiated by a modified particle spectrum.

6 General radiation effects in solar cells

6.1 Solar cell radiation damage

Solar cells, like all semiconductor devices, are subject to electrical degradation when exposed to particle irradiation. In terms of radiation damage to solar cells used in space, the primary particles of interest are electrons and protons. When these energetic particles are incident upon the solar cell material, they collide with the atoms of the crystal lattice of the solar cell. In these atomic collisions, energy is transferred from the incident particle to the target atom. This energy is transferred in one of two ways. The majority of the energy is transferred through ionization of the target atom, where electrons of the target atom absorb the transferred energy and are promoted to higher energy levels. The second energy transfer mechanism is through nonionizing events, which result in displacement of the target atom. If enough energy is transferred in a nonionizing event, then the displaced target atom may, in turn, displace other atoms, creating a cascade of displaced atoms. It is the displacement damage induced by the nonionizing interactions that causes solar cell electrical degradation.

When an atom is displaced in a lattice, the electron energy band structure of the material is disturbed, and localized energy levels can be created near the site of the defect. These defect energy levels can act to trap electrical charge carriers, thus restricting their ability to move through the material, which is characterized by a reduction in the minority carrier diffusion length. Since solar cell operation depends on the motion of photogenerated charge carriers through the material, these defect sites tend to degrade the solar cell performance.

The amount of displacement damage caused by an incident particle is a function of the type of incident particle (i.e. electron or proton), the particle energy, and the type of atoms that comprise the crystal lattice. The rate at which the incident particle transfers energy to the crystal lattice through nonionizing events is referred to as the nonionizing energy loss (NIEL). Electrons become more damaging as the incident electron energy increases. The opposite is true for protons, where the lower energy protons are the most damaging. Also, protons are significantly more damaging in comparison to electrons, primarily due to the increased proton size. There is a lower limit to displacement damage corresponding to the threshold energy for atomic displacements.

6.2 Radiation effects on solar cell cover

Although not specifically a solar cell radiation effect, it is appropriate in this document to note the effects of irradiation on solar cell coverglass material. Certain solar cell coverglass material has been shown to darken under irradiation thereby absorbing some of the incident light [4]. This increased light absorption can reduce the solar cell output in one of two ways: (1) reduction of the amount of light that reaches the cell, and (2) increased array operating temperature that reduces the cell electrical conversion efficiency.

7 Radiation test methods

7.1 General

As described in Clause 5, the space radiation environment consists of a spectrum of particle energies, and as described in Clause 6, solar cell radiation damage is energy dependent. Irradiation by a spectrum of particles in a laboratory is not practical; so most ground radiation testing is done using a monoenergetic beam of particles. Therefore, any space solar cell radiation testing shall be done in such a way as to enable extrapolation from monoenergetic radiation damage to damage produced by irradiation by a particle spectrum. This is typically done by using the ground test data to reduce the particle spectrum to a fluence of monoenergetic particles that produce an equivalent amount of damage. The determination of the equivalent fluence can be achieved in different ways, the primary of which are the JPL and NRL methodologies [2, 3, 5]. While it is beyond the scope of this document to discuss these data analysis methods, it is important that the method to be used for a specific experiment be chosen and well understood prior to performing any radiation testing. Similarly, it should be noted that this document is written to give guidelines on how to perform radiation testing on a space solar cell independent of the device technology. Differing cell technologies may exhibit differing radiation response characteristics that need to be understood in order to perform a meaningful test. Post irradiation annealing is one specific example. Silicon solar cells have been observed to anneal over time at room temperature after irradiation. It was found that the cell electrical output stabilized after a 24 h, 60°C anneal, so such a post-irradiation annealing stage was adopted as the

standard protocol for Si solar cells. Issues such as these must be researched and understood on a technology specific basis.

7.2 Electron irradiation

7.2.1 Temperature

Since by its nature, particle irradiation can heat the sample and since heating the sample can affect the nature and extent of the radiation-induced damage, the irradiation temperature must be maintained at a known temperature. This is typically achieved in two ways (1) limiting the particle flux and (2) mounting the samples on a temperature-controlled plate.

The exact temperature of the irradiation and accuracy of the temperature measurement should be determined with respect to the specific technology under test. To maintain consistency with most ground testing of space solar cells, irradiations are typically performed at room temperature. If there is a possibility of a temperature rise during irradiation, the test sample temperature should be held at 28°C, unless specified otherwise for a special situation.

7.2.2 Coverage area

Electron accelerators typically produce particle beams with a circular cross sectional area. To expose samples of larger area or to expose more samples in a single irradiation, it may be desired to increase the cross sectional area. One typical method for expanding the exposure area is to pass the particle beam through a thin foil that scatters the beam. When implementing a scattering foil, care shall be taken to ensure the proper particle energy and beam uniformity on target. Beam uniformity is discussed in the next subsection. Concerning the beam energy, the particles will lose energy as they pass through the foil. The amount of energy lost is dependent on the foil material, the foil thickness, the incident particle type, and the incident particle energy. The standard method is to use foils consisting of a single element, like Al or Cu, so that energy loss can be calculated and accounted for. Materials with complex internal structures, like composite graphite materials, are to be specifically avoided as their affect on the particle energy is difficult to quantify. For example, a 1 MeV electron will lose approximately 50 keV as it passes through a 0,127 mm thick Al foil, so when using such a scattering foil, the accelerator voltage is increased by 50 keV.

An alternative method for increasing the exposure area is to mount the samples on a rotating stage that periodically moves the samples through the beam. A standard implementation of this is to use a rotating wheel attached to a motor much like a phonograph record. When implementing this technique, care shall be taken to adjust the irradiation time to account for the duty cycle of the rotating stage, since each sample will be exposed only for a fraction of the irradiation time. This is achieved by calculating a constant scale factor based on the geometry of the mounting stage.

Because accelerator beam fluxes typically vary significantly over short time periods, large errors in flux and fluence can result without a continuous direct measurement method. This is especially true in the case of irradiating cells on a rotating stage. Therefore, special care should be taken in such cases to allow continuous monitoring of the flux, and integrating it over time to calculate fluence.

A third method of achieving beam uniformity over a large area is to use either magnetic or electrostatic deflectors to sweep the beam back and forth and up and down. Care must be taken to set the deflection frequencies so that the beam sweeps through many cycles (at least 100, but perhaps more if the beam spot size is small and the irradiation area is large). This is probably the best method to achieve a very uniform beam, but there is the danger of extremely high momentary flux densities and high localized heating over small areas. This method can be used for both electrons and protons.

7.2.3 Irradiation beam uniformity

To ensure uniform exposure of the solar cell to the electron irradiation beam, care shall be taken to ensure that the electron intensity is uniform over the entire area of the beam. Specification on the acceptable uniformity is dependent on the specific technology under study. However, experience has shown that 5 to 10% uniformity is both acceptable for valid radiation testing and reasonably achievable.

7.2.4 Flux levels

Most electron accelerators can operate over a wide range of fluxes. The flux is adjusted to obtain the desired total fluence in a desired amount of time. However, care must be taken since the incident electron beam can cause an increase in the solar cell temperature. As discussed in subclause 7.2.1, the temperature of the solar cells during irradiation should be measured. The typical range for electron flux is $10^9 - 10^{12}$ e/cm²/s. It should also be noted that for certain technologies, the magnitude of the flux may affect the amount of degradation observed due to dose rate effects. This is, again, a technology specific issue.

7.2.5 Vacuum

Electron irradiation may be performed under vacuum or in air. Scattering of the electrons in air results in an energy spread that is highly dependent on the incident energy and the path length of air traveled by the electrons.

7.2.6 Dosimetry

The fluence for electrons is typically measured using a Faraday Cup attached to a current integrator. The Faraday Cup shall be designed to suppress electron backscattering. This is typically achieved through grounding the external casing of the cup and by designing the cup geometry to maximize recapture of scattered electrons.

For accurate dosimetry with a Faraday Cup, the beam-line must be properly aligned. If the beam-line is not aligned properly, then the particles can scatter off the sidewalls prior to reaching the target plane. Scattering of the beam off of the beam line walls will degrade the particle energy. In such a case, the Faraday Cup may read a current indicative of the desired flux, but the energy content of particles will be degraded. Furthermore, if the aperture of the Faraday Cup is misaligned with the incident beam then the aperture area normal to the beam is decreased and less beam will enter the cup, so in this case the current will not be indicative of the desired flux.

7.3 Proton irradiation

7.3.1 General

All of the points from the preceding section also apply to proton irradiation except as stated in the following.

7.3.2 Coverage area

Low energy proton irradiation (<10 MeV) shall be performed in vacuum (see subclause 7.3.3), which puts more constraints on the material used as scattering foils. If the beam coverage area is to be enlarged using scattering foils as discussed in subclause 7.2.2 above, then the foil material shall be chosen so that it can be made thin (to lessen the proton energy loss) but strong so it can withstand vacuum and handling. The foil material must also have a high heat conductivity and a high melting point in order to withstand the high currents produced by the proton irradiation. The thickness uniformity of the foil material shall be also be verified, as significant variations in thickness across a foil have been observed, which can significantly impact the proton beam emerging from the foil.

7.3.3 Vacuum

Because protons experience significant scattering in air, low energy proton irradiations shall be done in vacuum. The pressure should be in the range of 10^{-5} Torr or lower.

7.4 Annealing

Some solar cell types demonstrate electrical parameter improvement after a short time anneal or light soak (for example Silicon). It is recommended that an annealing schedule be considered and investigated for a given solar cell type and application.

8 Test report

The radiation test report shall normally include at least the following information :

- 1) a title (i.e., Test Report)
- 2) tested date
- 3) name and address of radiation test facility, and location where the tests and/or measurements were carried out, if difference from the address of the facility
- 4) irradiated conditions (i.e., irradiated particle, irradiated energy, energy tolerance, irradiated fluence, flux density, dose rate, and temperature, etc.)
- 5) used AM0 standard solar cell (i.e., non-irradiated cell or irradiated cell)
- 6) annealing conditions (i.e., temperature storage or light soaking, etc.)
- 7) measurement equipment and its electrical performance
- 8) number of samples for each irradiated fluence

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